

REMARKS/ARGUMENTS

The previous rejection over the combination of Takehisa and Strebelle has been withdrawn in view of Applicants' amendment limiting the claims to zeolite catalyst. See point 6. at page 5, top, of the Official Action. Applicants appreciate the withdrawal of this rejection. However, it appears from point 5. of the Official Action, beginning at the bottom of page 3 thereof, that these same references have been applied against the claims in an obviousness rejection, albeit with different designations regarding primary and secondary reference. To the extent that this understanding is correct, this rejection is traversed.

At page 4, line 3 of the Official Action Takehisa is described as "analogous" to the present invention.¹ However, at page 3, lines 10-11 of the same Official Action it is recognized that Takehisa uses an alkyl hydroperoxide as the oxidizing agent, rather than hydrogen peroxide, as claimed. In addition, at page 5, 4-5 lines up from the bottom, the Official Action recognizes that Takehisa uses a catalyst that is different from that presently claimed (zeolite). Thus, in a three component reaction - reactant, catalyst and oxidizing agent - Takehisa differs significantly in its choice of two of the three. This is not an analogous reaction, especially when viewed in light of the prior bias against the interaction between a Ti/SiO₂ catalyst as used in Takehisa² and the presently claimed oxidizing agent, as explained below.

Submitted herewith is an article by Sheldon which, beginning at the fourth paragraph on the right hand side of page 485 and continuing to page 486, describes the historical difficulties encountered in using aqueous hydrogen peroxide (the presently claimed oxidizing agent) with Ti/SiO₂ catalysts like those used in Takehisa. Such problems apparently were avoided by Takehisa by the use of alkyl hydroperoxide as the oxidizing agent, rather than

¹ Applicant has previously filed an English version of Takehisa (JP 04327582).

² See paragraph [0015] of the English translation for the preparation of a Ti/SiO₂ catalyst in Takehisa.

hydrogen peroxide. Clearly, alkyl hydroperoxide and hydrogen peroxide are *not* interchangeable in this art, including specifically in the presently claimed reaction of allyl chloride with an oxidizing agent.

Strebelle is also quite different from Takehisa. In Strebelle epichlorohydrin is made by reacting allyl chloride with a peroxide compound in the presence of water, a catalyst and a diluent. See the paragraph bridging columns 1 and 2 of the reference. Zeolite catalysts can be used (column 2, lines 3ff) and the peroxide compound can include hydrogen peroxide (column 2, lines 29-31).

The advance described in Strebelle is the elimination of unwanted organochlorine products (column 1, lines 25-31) whereas the purpose of the purification in Takehisa is described in paragraph [0004] and [0005] of the English version: because olefinic compounds have similar properties to the product epichlorohydrin, it is better to remove such olefinic compounds from the starting materials rather than wait and try to remove them from the product epichlorohydrin.

Thus, Takehisa and Strebelle are quite different from one another: different catalysts are used, different oxidants are used, and different impurities are removed. As such, the references are not combinable, and even when combined do not teach a process as claimed: there would be no reason to perform Takehisa's pre-reaction removal of 1,5-hexadiene in the Strebelle process because Strebelle focuses on chloro impurities, not olefin impurities. While the Examiner seems to discount this point, it is nevertheless the case that **there would be absolutely no expectation of an improvement in zeolite catalyst life upon combination of the teachings of these references.**

At the top of page 6 of the Official Action the position is taken that Applicants' demonstrated improvement in catalyst life is "inherent." However, inherency applies only in anticipation rejections, while the rejection at hand is one for obviousness. In such a situation

it is legal error for the Office to conclude that the unexpected results flowing from the invention are inherent in the Examiner's prior art construct as this is of course the case - the Examiner believes he has constructed Applicants' exact invention by combining prior art references. The question to be asked is whether the results are unexpected in view of the references, and in this case the answer is yes.

Catalyst deactivation is notoriously unpredictable, and can occur as a result of poisoning, sintering, leaching, blockage to active sites, etc. Individual process conditions and chemical interactions between the catalyst and the other components of the reaction determine deactivation, and thus are not predictable or applicable from one system to the next.

In this case Applicants' unexpected improvement in catalyst life has been amply demonstrated in the present specification. As shown in the Examples beginning at page 7, when zeolite catalysts are used and the allyl chloride is free of 1,5-hexadiene according to the present claims (a combination nowhere provided in any single reference applied) a dramatic and sustained improvement in catalyst life and, consequently, degree of conversion, is obtained. For example, and as shown in Table 1 at specification page 7, production using normal allyl chloride is exhausted at 27 hours, while allyl chloride according to the present invention remains active at 147 hours of reaction time. Similar results are shown in Tables 2 and 3, all of which show an impressive extension of catalyst life and conversion percent.

Therefore, because neither Takehisa, Strebelle, nor their combination disclose or suggest such an advantage, even if the references could be combined in a manner such that the present claims were suggested, which they cannot, Applicants' invention still is patentable in view of the demonstration of superior results.

Accordingly, and because the references, even when combined, fail to suggest the present invention, and because Applicants have shown significantly superior results and an

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important advantage undisclosed and unpredicted by any applied reference, Applicants respectfully request the reconsideration and withdrawal of the outstanding rejections, and the passage of this case to Issue.

Respectfully submitted,

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Heterogeneous Catalysts for Liquid-Phase Oxidations: Philosophers' Stones or Trojan Horses?

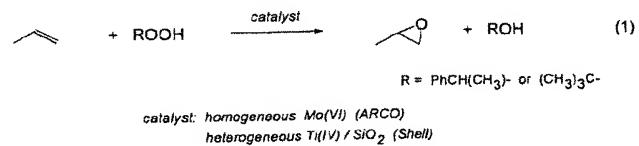
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Introduction

In the early seventies one of us¹ was involved in the development of the heterogeneous Ti(IV)/SiO₂ catalyst which forms the basis of the Shell process for the epoxidation of propylene with ethylbenzene hydroperoxide (reaction 1).²



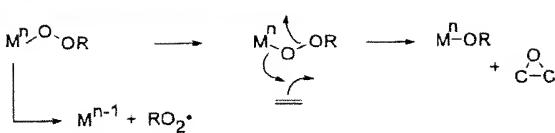
Roger A. Sheldon (1942) is a native of Nottingham (UK). He received a Ph.D. in chemistry from the University of Leicester (UK) in 1967. Following a postdoctoral sojourn with Jay Kochi he was with Shell Research, Amsterdam, from 1969 to 1980. From 1980 to 1990 he was R&D director of DSM Andeno (Venlo, The Netherlands). In 1991 he was appointed Professor of Organic Chemistry at Delft University of Technology. His research interests are mainly concerned with the application of catalytic methods, in particular catalytic oxidations using homogeneous, heterogeneous and biocatalysts, in organic synthesis. He is the author/editor of several books on the subject of catalysis, notably "Metal Catalyzed Oxidations of Organic Compounds" which he coauthored with Jay Kochi.

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Isabel W. C. E. Arends was born in the Netherlands in 1966 and studied chemistry at the University of Leiden (The Netherlands) where she received her Ph.D. in 1993 on the thermolysis of arene derivatives with coal-type hydrogen donors under the supervision of R. Louw and P. Mulder. Postdoctoral work followed with K. U. Ingold at the National Research Council in Canada on liquid phase oxidations catalyzed by iron-biomimetic complexes. She joined the group of R.A. Sheldon in 1995 and her research interests include metal-catalyzed selective oxidations, redox molecular sieves, and in particular catalytic oxidations with biomimetic vanadium systems.

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Scheme 1



Halcon³ and ARCO^{4,5} workers had previously found, independently, that soluble compounds of early transition metals, e.g., Mo, W, Ti, and V, catalyze reaction 1. The mechanism of catalysis involves withdrawal of electrons from a coordinated alkylperoxy moiety, thereby increasing the electrophilic character of the peroxidic oxygens, i.e., the metal ion acts as a Lewis acid. Hence, effective catalysts are both a strong Lewis acid and a weak oxidant in their highest oxidation state. The latter criterion is necessary in order to minimize competing one-electron oxidation of the ROO ligand leading to homolytic decomposition of ROOH (see Scheme 1).

These criteria are best met by molybdenum(VI), and soluble molybdenum compounds exhibit the best combination of activity and selectivity.^{6,7} Soluble titanium(IV) compounds, on the other hand, are rather mediocre catalysts for reaction 1. In contrast, Ti(IV)/SiO₂ exhibits selectivities comparable to homogeneous molybdenum and (for a heterogeneous catalyst) high activities.⁸ The superior catalytic activity of Ti(IV)/SiO₂ was attributed to both an increase in Lewis acidity of the Ti(IV), owing to electron withdrawal by silanol ligands, and to site isolation of discrete Ti(IV) centers in the silica lattice preventing oligomerization to unreactive μ -oxo species (which readily occurs with soluble Ti(IV) compounds).

Furthermore, it was demonstrated that only the combination of titanium(IV) with silica affords a stable heterogeneous catalyst; all other combinations, e.g., Mo(VI), W(VI), V(V), etc., on silica, gave rapid leaching of the metal ion.

One property which soluble Ti(IV) compounds and Ti(IV)/SiO₂ share is a marked sensitivity toward deactivation by strongly coordinating ligands, especially water.⁹ For this reason Ti(IV)/SiO₂ is an ineffective catalyst for epoxidations with aqueous hydrogen peroxide. Hence the appearance in the mid-eighties of Enichem patents¹⁰ describing the remarkable catalytic activity of titanium(IV) silicalite (generally known as TS-1) in, inter alia, the selective epoxidation of olefins under very mild conditions with 30% aqueous hydrogen peroxide (Figure 1) was greeted with some scepticism. Thus, two materials, Ti(IV)/SiO₂ and TS-1, having roughly the same elemental composition, i.e., 2% Ti in SiO₂, exhibited totally different catalytic properties.

Initial attempts by various groups to reproduce the Enichem results were largely unsuccessful. However, once it became clear that certain parameters in the synthesis

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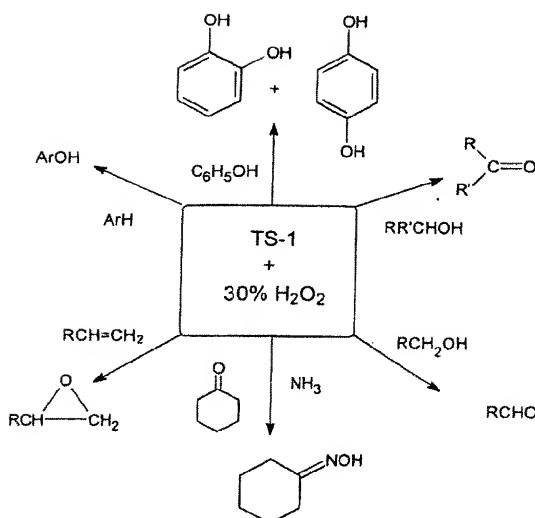


FIGURE 1. Oxidations catalyzed by TS-1.

of TS-1, e.g., the absence of traces of alkali metal ions in the tetrapropylammonium hydroxide template, are critical, its remarkable activity was confirmed.¹¹ Furthermore small catalyst particles are necessary to avoid diffusion limitations.¹²

It was subsequently shown, using various spectroscopic techniques,¹¹ that TS-1 contains titanium isomorphously substituted for silicon in the framework of silicalite-1, a hydrophobic molecular sieve possessing a three-dimensional system of intersecting elliptical pores with diameters of 5.3×5.5 and $5.1 \times 5.5 \text{ \AA}$.¹³ Its remarkable activity in oxidations with aqueous H_2O_2 is due to site isolation of Ti(IV) centers in the hydrophobic pores of silicalite which allows for the simultaneous adsorption of the hydrophobic substrate and the oxidant. This importance of fine-tuning of the hydrophobicity of the catalyst was clearly demonstrated by Klein and Maier¹⁴ in the case of titanium-containing microporous glasses, where the activity increased with the hydrophobicity. The introduction of titanium into the silicalite framework increases its

hydrophilicity, but the resulting material is still highly hydrophobic as measured by its hydrophobicity index, HI.¹⁵⁻¹⁷ Thus Weitkamp et al.¹⁶ measured the HI of a range of TS-1 samples and showed that it decreased linearly with titanium content for $n_{\text{Si}}/n_{\text{Ti}} > 40$, as was shown in a qualitative way also by others.^{18,19}

Confinement of the active site in a cavity of molecular dimensions means that there is not enough room for the simultaneous presence of substrate and (several) solvent molecules in the active site, thus creating quasi vapor phase conditions conducive to fast reactions. Similar arguments were forwarded by Dewar²⁰ to explain the high activity of enzymes.

On reflection it occurred to us that TS-1 was perhaps the proverbial tip of an iceberg, i.e., the progenitor of a broad family of novel catalytic materials for use in selective liquid phase oxidations. Indeed, this subsequently proved to be the case, and we coined the generic term redox molecular sieve to describe such materials.^{21,22}

Redox Molecular Sieves

Molecular sieves are commonly referred to as zeolites or zeotypes, which are crystalline oxides comprising corner sharing TO_4 tetrahedra ($\text{T} = \text{Si}, \text{Al}, \text{P}$, etc.) and consisting of a regular array of micropores of molecular dimensions (4–13 Å). In zeolites the centers of the TO_4 tetrahedra are occupied by silicon and aluminum atoms. The different valences of Si (tetravalent) and Al (trivalent) produce an overall negative charge for each incorporated aluminum atom. These negative charges can be balanced by protons (leading to Brønsted acids) or other cations. Substitution of the trivalent atoms in the zeolite framework by tetravalent atoms such as silicon or titanium produces (metallo)silicalites with an electrically neutral, hydrophobic framework. Aluminophosphates (AlPO's) possess a neutral, hydrophilic framework ($\text{P:Al} = 1:1$), and substitution of the pentavalent phosphorus by silicon produces silicoaluminophosphates SAPO's with a negatively charged framework. Incorporation of redox metals into molecular sieves (see Figure 2) affords potentially

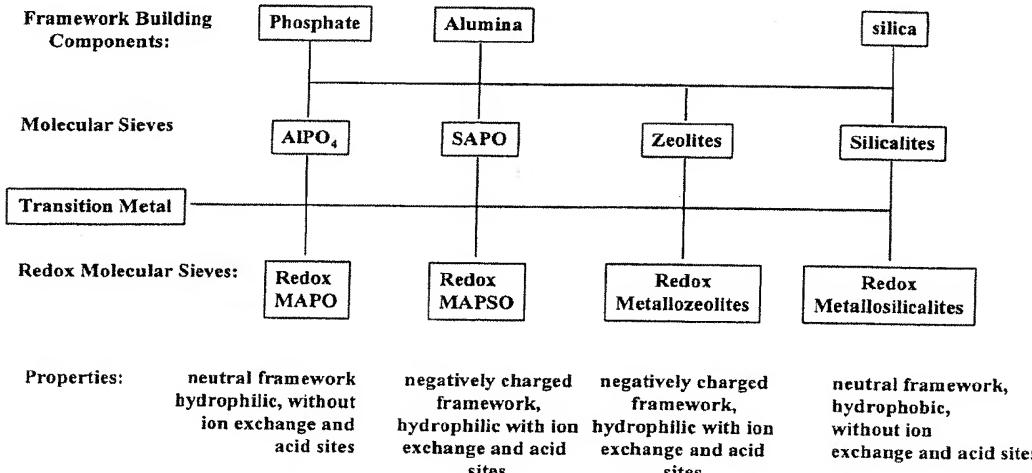


FIGURE 2. Types and properties of redox molecular sieves.

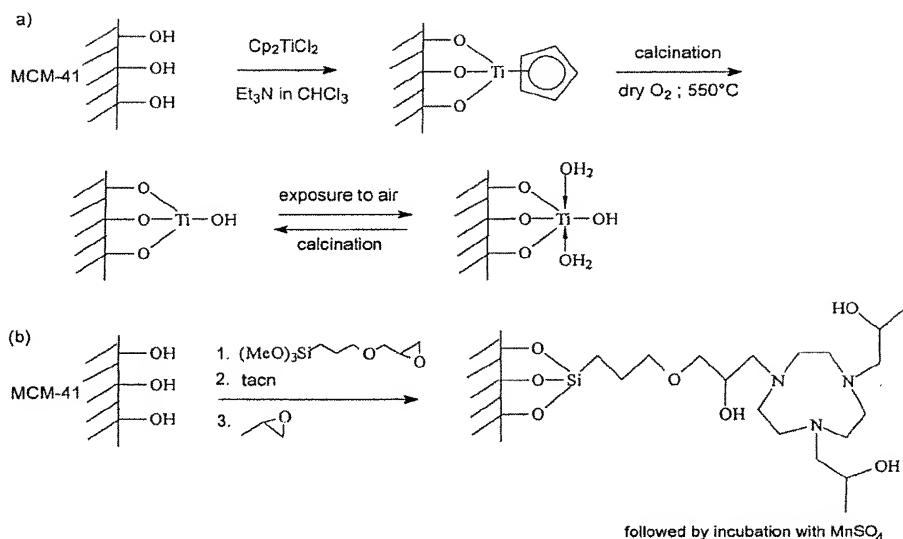


FIGURE 3. Grafting (a) and tethering (b) of metal complexes with molecular sieves.

interesting heterogeneous oxidation catalysts.²³ By a suitable choice of molecular sieve, one is able to influence which molecules have ready access to the active site on the basis of their size and/or hydrophobic/hydrophilic character. Such materials bear a distinct resemblance to redox enzymes in which the protein mantel plays an analogous role. It is perhaps not surprising, therefore, that they are sometimes referred to as "mineral enzymes".

Synthesis of Redox Molecular Sieves

Molecular sieves are synthesized by so-called hydrothermal synthesis in which a sol-gel is produced from sources of the building blocks (e.g., $\text{Si}(\text{OEt})_4$, Al_2O_3 , H_3PO_4) and subsequently allowed to crystallize at elevated temperatures (generally 180–200 °C) and autogenous pressure in the presence of a structure directing agent (template), usually an amine or tetraalkylammonium salt. The as-synthesized material is subsequently calcined at ca. 500 °C to destructively remove the template. If a redox metal salt or complex is added during gel formation it can be incorporated into the framework of the molecular sieve. Alternatively, redox molecular sieves can be prepared by postsynthesis modification.^{24–26} Framework aluminum atoms can be substituted, for example, by treatment with TiCl_4 in the vapor phase.²⁴ Borosilicates are more amenable to postsynthesis modification than the isomorphous zeolites since boron is readily abstracted from the framework under mild conditions,²⁷ followed by reoccupation of the formed silanol nests by Ti.²⁸

A completely different postsynthesis approach consists of encapsulating a bulky metal-ligand complex, e.g., a metallophthalocyanine, within cages present in certain zeolites.^{29–31} These so-called ship-in-a-bottle catalysts are prepared by first introducing the metal into the zeolite, after which the ligand is synthesized, *in situ*, to give a metal complex which is physically trapped within the

zeolite lattice. Alternatively, metal complexes have been applied as templates during zeolite synthesis.³⁰

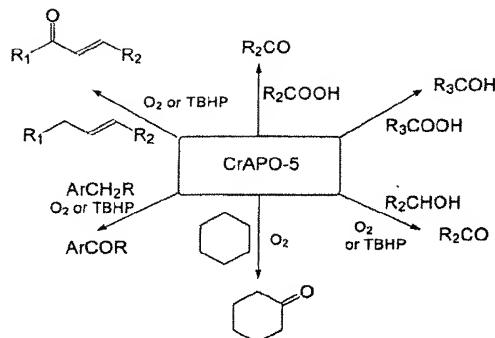
The development of mesoporous molecular sieves such as MCM-41, which are amorphous silicates³² containing a regular array of hexagonal ordered mesopores, extended the scope to much larger substrates and guest complexes. In this case metal complexes^{33,34} can be grafted or tethered (via a spacer ligand) to the internal surface (see Figure 3).

Titanium-Substituted Molecular Sieves

A serious drawback of TS-1 is its restriction to substrate molecules with kinetic diameters³⁵ $\leq 5.5 \text{ \AA}$ (see above). For example, 1-hexene is readily epoxidized with aqueous H_2O_2 at 50 °C whereas cyclohexene is essentially unreactive. Molecular graphics indicate that cyclohexene can just fit into the pores of TS-1 but that it is difficult to accommodate the transition state for oxygen transfer from a peroxotitanium(IV) species to the double bond. By the same token, TS-1 does not catalyze epoxidations with the more bulky *tert*-butyl hydroperoxide (TBHP); i.e., TS-1 exhibits complementary catalytic properties to the Ti(IV)/ SiO_2 catalyst.

To circumvent this size restriction, many groups have incorporated titanium in larger molecular sieves.^{11,23,36} For example, Corma and co-workers³⁷ synthesized titanium-substituted zeolite beta (pore diameter up to 7.6 Å) and showed that it catalyzed the oxidation of cyclohexene and 1-hexene, with aqueous H_2O_2 in methanol, at roughly the same rate. However, in contrast to reactions with TS-1, the main product was the glycol monomethyl ether, resulting from acid-catalyzed ring opening of the epoxide by the methanol solvent.

We subsequently showed that ring opening could be largely circumvented by neutralizing the Brønsted acid (aluminum) sites by ion exchange with an alkali metal

**FIGURE 4.** Oxidations catalyzed by CrAPO-5.

acetate and recalcination.³⁸ Similarly, 1-octene underwent selective epoxidation with TBHP in the presence of alkali metal exchanged titanium beta.³⁹

Similarly, titanium-substituted MCM-41^{40,41} and a titanium-grafted MCM-41 (see Figure 3)³³ were shown to catalyze the epoxidation of bulky olefins, such as pinene and norbornene, with TBHP. In the case of titanium-grafted on MCM-41, the importance of hydrophobicity in the system was demonstrated by the fact that use of a more hydrophobic alkyl hydroperoxide, 2-methyl-1-phenyl-2-propyl hydroperoxide, increased the reaction rate.⁴²

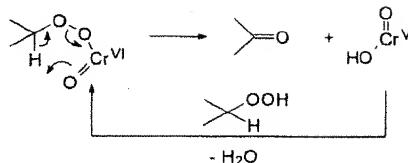
Other Redox Metals

Following the success of titanium-substituted molecular sieves, a variety of metals have been incorporated into molecular sieve frameworks and the resulting materials tested as catalysts for liquid-phase oxidations.²³ For example, Sn(IV)⁴³ and Zr(IV)^{44,45} substituted silicalite exhibited similar catalytic properties to TS-1, albeit with lower activities.^{46,47} Vanadium-substituted silicalite and aluminophosphates have also been extensively investigated.^{11,48,49}

We have carried out detailed investigations of chromium-substituted molecular sieves.^{50,51} These were of particular interest because chromium(VI) reagents are widely used as stoichiometric oxidants in organic synthesis⁵² or as homogeneous catalysts in the presence of alkyl hydroperoxides as terminal oxidant.⁵³ Moreover, chromium(VI) typically catalyzes oxidations via an oxometal mechanism, in which chromyl (CrO_2^{2+}) species are the active oxidants. Hence, chromium-substituted molecular sieves are expected to catalyze different oxidative transformations to titanium(IV) which involves a peroxometal mechanism.

Indeed, we found that CrS-1, CrAPO-5, and CrAPO-11 catalyze a variety of oxidations typical of oxometal oxidants, e.g., benzylic and allylic oxidations (Figure 4) using TBHP or O_2 as the terminal oxidant. A plausible mechanism for these transformations involves oxidation of the substrate by $\text{Cr}^{\text{VI}}=\text{O}$ followed by reoxidation of the resulting Cr^{IV} by TBHP, or, in the case of reactions with O_2 , the hydroperoxide derived from (chromium-catalyzed) autoxidation of these substrates.

One of the first reactions which we studied was the decomposition of cyclohexyl hydroperoxide (CHHP) to a

**FIGURE 5.** Chromium-catalyzed decomposition of alkyl hydroperoxides.

mixture of cyclohexanone and water. Both CrAPO-5 and CrS-1 were efficient catalysts for this reaction,⁵⁴ which is of importance in the manufacture of cyclohexanone by autoxidation of cyclohexane. CrAPO-5 gave cyclohexanone in 86% selectivity, together with 13% cyclohexanol, at 87% conversion in 5 h at 70 °C in cyclohexane. A plausible mechanism to explain the high selectivity to cyclohexanone is shown in Figure 5.

Cyclohexanol presumably results from cyclohexyloxy radicals formed in competing one-electron redox reactions of chromium with the hydroperoxide.⁵⁵ Thus, tertiary hydroperoxides, which cannot undergo the heterolytic decomposition shown in Figure 5, afforded the corresponding alcohols.

To confirm that the reaction takes place in the micropores of CrAPO-5, we performed experiments with the bulky tertiary hydroperoxide, triphenylmethyl hydroperoxide (TPMHP) which is too large to access the micropores.⁵⁴ We found that homogeneous $\text{Cr}(\text{acac})_3$ and supported $\text{Cr}_2\text{Cl}_2/\text{SiO}_2-\text{Al}_2\text{O}_3$ were effective catalysts (75 and 72% decomposition in 2 h at 70 °C in dichloroethane). In contrast, CrAPO-5 gave only 1% decomposition of TPMHP which led us to conclude that the reaction occurred exclusively in the micropores and that no leaching of the chromium occurred. This subsequently proved to be a misinterpretation of the results (see below).

Philosophers' Stones or Trojan Horses? The Question of Leaching

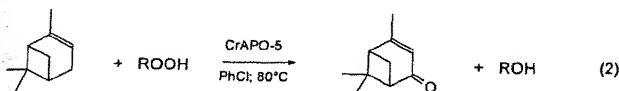
Elsewhere we have referred to zeolites, and by implication redox molecular sieves, as the philosopher's stone of modern chemistry.²³ There is no doubt that they exhibit interesting activities and selectivities, but stability is also a *sine qua non* for industrial utility. A heterogeneous catalyst which simply releases its active species into solution—like Greek warriors from the Trojan horse—is likely to have limited practical utility. Hence, it is surprising that most papers pay scant attention to this aspect. In some cases⁵⁶ no recycling experiments are reported. Moreover, as we shall now show, even the conventional recycling of catalysts several times without significant loss of activity is by no means sufficient proof of heterogeneity.

One can envisage three different scenarios in the context of leaching:

- The metal leaches but is not an active homogeneous catalyst.
- The metal leaches to form an active homogeneous catalyst.
- The metal does not leach and the observed catalysis is truly heterogeneous in nature.

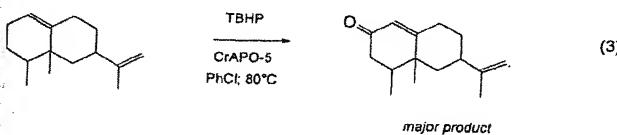
Since titanium(IV) is a poor homogeneous epoxidation catalyst,⁵⁷ the remarkable activity observed with TS-1, and to a lesser extent with other titanium-substituted molecular sieves, is clearly heterogeneous in nature. Hence, titanium falls into category A or C. Not being privy to the detailed information, we can only assume that extensive testing of TS-1 (and Ti(IV)/SiO₂) has demonstrated its stability toward leaching under operating conditions, i.e., that it falls into category C. We note, however, that this does not rule out a slow but practically insignificant leaching. Judgment on the many other titanium-substituted molecular sieves regarding whether they are category A or C has to be suspended in lieu of appropriate longevity tests. The same probably applies to analogous Zr(IV)-, Sn(IV)-, and Fe(III)-substituted molecular sieves.

Category B is the difficult one to assess; i.e., when a particular metal ion exhibits (high) catalytic activity in solution, what can be construed as rigorous proof of heterogeneity? A particularly poignant example is provided by chromium. Recently we returned to the question of leaching in a study of the allylic oxidation of α -pinene to verbenone with TBHP in the presence of chromium-substituted molecular sieves (reaction 2).⁵⁸



To test for leaching we filtered the catalyst, e.g., CrAPO-5, after 30 min (ca. 25% pinene conversion) and allowed the filtrate to react further. Filtration was performed at the reaction temperature (80 °C) in order to avoid read-sorption of solubilized chromium on cooling (this later proved to be important but for a different reason). Indeed, we found that after hot filtration the mother liquor (filtrate) reacted further at roughly the same rate as that observed when the catalyst was not filtered. In contrast, if the mixture was allowed to cool to ambient temperature prior to catalyst filtration, the procedure generally followed when testing for leaching, little further reaction was observed. On the basis of these results we concluded that chromium is leached from CrAPO-5 and that the observed catalysis is (predominantly) homogeneous in nature.

We subsequently compared the allylic oxidation of α -pinene with a bulky hydroperoxide: triphenylmethyl hydroperoxide (TPMHP) (reaction 2, R = Ph₃C) and a bulky olefin (valencene) with TBHP (reaction 3).



If the reaction took place in the micropores, one would expect to observe no reaction in both cases, since both TPMHP and valencene are too bulky to access the micropores of CrAPO-5. However, we observed facile conversion of valencene with TBHP but virtually no conversion of pinene with TPMHP. The most plausible explanation

for these observations is that soluble chromium is responsible for the observed catalysis and that it is leached by reaction with the hydroperoxide. Support for this interpretation was obtained in experiments where CrAPO-5 was pretreated with TBHP, the mixture filtered, and pinene added to the mother liquor, which resulted in facile oxidation. In contrast, when the catalyst was pretreated with pinene and filtered, no reaction was observed when TBHP was added to the filtrate. Based on these results, the earlier observations of no decomposition of TPMHP in the presence of CrAPO-5 (see above) could be reinterpreted to mean exactly the opposite of our initial interpretation.

Having established that soluble chromium is responsible for the observed catalysis, the next question was: how much chromium is leached? By using a sensitive colorimetric test for chromium(VI), we were able to show that 0.3% of the 0.88% chromium (i.e., 0.0026% of the catalyst's weight) present in CrAPO-5 was leached during reaction, corresponding to a substrate/catalyst (S/C) ratio of 17 000 or 1–2 ppm Cr in the filtrate.⁵⁹ Analogous experiments with CrAPO-11 and samples of CrS-1 prepared by different procedures showed that the extent of chromium leaching varied between 0.3 and 34%, increasing markedly with decreasing crystallite size of the catalysts.

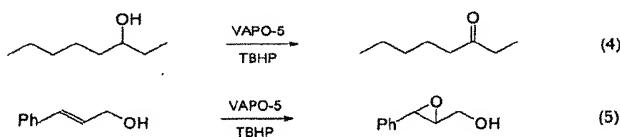
We furthermore showed that if the filtrate was allowed to cool to ambient temperature, the solubilized chromium was present only in the trivalent state. We subsequently carried out oxidations with soluble chromium(VI), (py)₂Cr₂O₇, and chromium(III), Cr(acac)₃, catalysts at various S/C ratios. When chromium was added as Cr(VI), the reaction always started instantaneously. This was also the case with Cr(III) at low S/C ratios (≤ 10), but induction periods of 5, 90, and 300 min were observed for S/C = 100, 1000, and 10,000, respectively. Combination of these results with the observation (see above) that on cooling the filtrate from the reaction temperature to ambient results in reduction of Cr(VI) to Cr(III) provides an explanation for the observed difference in the hot and cold filtration experiments. Apparently on cooling the reaction mixture, Cr(VI) continues to oxidize substrate but is not reoxidized by TBHP and, after filtration of the catalyst, only Cr(III) is present in the filtrate, at very low concentrations (S/C = 17 000 for 0.3% Cr). This results in a very long induction period which would lead to the erroneous conclusion that no leaching had occurred.

We subsequently compared the activity of a filtrate obtained from TBHP treatment of CrAPO-5, followed by hot filtration, with that of a solution containing (py)₂Cr₂O₇ in an amount corresponding to S/C = 17 000. The reaction profile was almost identical (the soluble Cr actually showed a slightly higher rate) which leads to the inevitable conclusion that all of the observed activity can be attributed to homogeneous Cr(VI) leached from the CrAPO-5 by reaction with TBHP.

We also call into question the common practice of comparing activities of putative heterogeneous catalysts with their homogeneous counterparts at (much) higher

concentrations. When a similar level of activity is observed with the homogeneous catalyst only at significantly higher concentrations than could have been (were) leached, this is proffered as evidence in support of the catalysis being (predominantly) heterogeneous. However, this assumes a linear relationship between catalyst activity and catalyst concentration. In a comparison of a CrS-1 sample and CrAPO-5, which gave 34 and 0.3% leaching, respectively, we observed a much smaller difference in rate (in the oxidation of α -pinene with TBHP) than the expected factor of 100. Subsequent measurements of turnover numbers at 30% pinene conversion, with homogeneous chromium(VI) at S/C ratios varying from 10^2 to 10^5 , revealed a nonlinear relationship between rate and catalyst concentration; the chromium was relatively more active at lower concentrations. This suggests that active monomeric chromium species are in equilibrium with less active dimers or oligomers in solution.

On the basis of our extensive studies, we conclude that chromium-substituted molecular sieves clearly belong to category B. What about other redox metal ions? van Hooff and co-workers⁶⁰ carried out a detailed investigation of VAPPO-5 catalyzed oxidation of 3-octanol and epoxidation of 3-phenyl-2-propenol with TBHP (reactions 4 and 5). By filtering the reaction mixture at the reaction temperature and allowing the filtrate to react further, they were able to show that leached vanadium accounted for the observed catalysis.



Similarly, the reported catalysis of oxidations with TBHP in the presence of vanadium silicalites, VS-1,¹¹ or VS-2⁴⁸ is almost certainly homogeneous in nature. A similar observation was made by Sayari and co-workers⁶¹ for V-HMS molecular sieves during oxidation reactions with dilute H_2O_2 . Indeed, we observed leaching of metal during oxidation reactions in all vanadium- and chromium-substituted molecular sieves that we have studied.⁶²⁻⁶⁴ For example, we synthesized V- and Cr-MCM-41⁶⁴ and showed that, after pretreatment with a solution of the oxidant (H_2O_2), the filtrate had a similar activity to that observed without filtration. In contrast, with Ti-MCM-41 the filtrate was not active and no metal loss was detected.

Similarly, we have shown, by performing appropriate filtration experiments, that catalysis of epoxidations (with TBHP) by zeolite Y encapsulated vanadium-Schiff's base complexes is due to leached vanadium.⁶⁵

Are Titanium Silicalites Unique?

Notwithstanding the plethora of studies devoted to redox molecular sieves,²³ the remarkable activity and stability of TS-1 have yet to be emulated. What is unique about TS-1? First, isomorphous substitution of titanium(IV) in

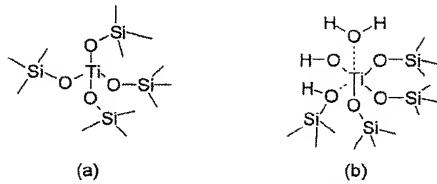


FIGURE 6. Ti in tetrahedral (a) and octahedral (site-defect) (b) positions of silicalite.

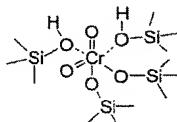


FIGURE 7. Cr attached to defect sites of silicalites.

tetrahedral framework positions appears to be essential. Perego et al.⁶⁶ reported that a maximum of 2.4 Ti atoms per unit cell (Si/Ti = 39) can be incorporated in the silicalite framework. Although other authors have claimed the preparation of TS-1 with higher Ti content, there are doubts regarding whether all of the Ti is in framework positions.¹¹

Tetrahedral coordination of Ti(IV) in framework positions can be confirmed using, e.g., EXAFS, UV/vis spectroscopy, and other methods.^{67,68} The presence of the 960-cm^{-1} peak in vibrational spectra of Ti sieves is not a good characteristic for isomorphous substitution of titanium; Smirnov⁶⁹ has calculated that this band can be assigned to a local Si–O vibration. We investigated TS-1 and Ti-beta samples with Si/Ti ratios < 40 and observed two different Ti species using UV/vis. One, characterized by a band at 212 nm,⁷⁰ could be assigned to tetrahedral Ti(IV) (Figure 6a) while the other, characterized by a band at 250 nm, was attributed to octahedral Ti(IV) in defect sites (Figure 6b) or to amorphous oligomeric Ti–O–Ti species.⁷⁰ Samples of TS-1 exhibiting the 250 nm band leached titanium when used as catalyst for cyclohexane oxidation with H_2O_2 , probably due to complexation of titanium by carboxylic acids formed by overoxidation.

With chromium and vanadium the situation is more complicated. In the as-synthesized materials they are present as Cr(III) and V(IV), respectively. Both Cr(III) and V(IV) can isomorphously substitute for Si(IV) or Al(III) in the silicalite, AlPO or SAPO⁷¹ framework, respectively. However, on calcination the chromium and vanadium are oxidized to Cr(VI) and V(V), respectively. Since chromium(VI) is presumed to always contain two extraframework Cr=O bonds, it can only be anchored to the framework at defect sites (see Figure 7). In this way chromium(VI) is attached to the surface by only two M–O bonds, and it is therefore perhaps not surprising that leaching is facile.

Thus, in a study of titanium(IV) silsesquioxanes, Abbenhuis et al.^{57a} showed that at least three Ti–O–Si bonds are necessary for stability. This situation is extant in TS-1 where the mechanism of oxidation most likely involves conversion of a Ti–O–Si or Ti–O–H group to Ti–OOR ($R = H$, alkyl) which is still bonded to three silanoxy groups (Figure 8).⁷² Similarly V $=$ O ions appear to be

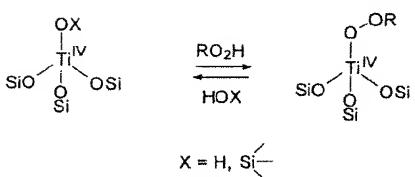


FIGURE 8. Activation of isomorphously substituted titanium.

attached to, e.g., the silicalite framework at defect sites¹¹ and is, hence, susceptible to leaching.

The synthesis of MoS-1 has recently been described.⁵⁶ By analogy with chromium this would be expected to consist of Mo^{VI}O₂ species attached to framework defect sites. The authors reported that the material was an active catalyst for the chemoselective oxidation of thioethers to the corresponding sulfoxides. However, no experiments were performed to establish the homogeneous or heterogeneous nature of the observed catalysis. Moreover, we note that oxidations of thioethers with H₂O₂ proceed readily under the prescribed conditions even in the complete absence of a catalyst.

Isomorphous substitution of tetrahedral Mn(II),⁶⁴ Co(II),^{63,64,73} and Fe(III)^{64,74} into various molecular sieves has been reported. After calcination manganese and iron are present in the trivalent state. The oxidation state of cobalt in CoAPO after calcination is still a matter of debate, however.^{75–79} Evidence has been presented in favor of both Co(III)^{75–77} and Co(II).^{78,79} It is also worth noting that tetrahedral Co(III) is energetically highly unfavorable (all known Co(III) complexes are octahedral). Although Fe(III) is not further oxidized on calcination, we observed for Fe-ZSM-12⁶² and Fe-MCM-41⁶⁴ that the crystals change their color from white to brown, indicating the formation of extraframework iron oxide. When the template molecules were removed by extraction, rather than calcination, e.g., with MnAPSO-37 and FeAPSO-37,⁷⁴ we observed no extraframework species and no metal leaching. Interestingly, however, the resulting materials were also completely inactive oxidation catalysts.

Conclusions and Prospects

Redox molecular sieves and grafted mesoporous materials, particularly titanium-substituted materials, undoubtedly have enormous catalytic potential in organic synthesis.²³ They catalyze a variety of synthetically useful oxidative transformations with environmentally and economically attractive oxidants. Their pore sizes and hydrophobic or hydrophilic properties endow them with special capabilities compared to analogous homogeneous catalysts. Moreover, they are readily recovered by simple filtration.

However, the initial euphoria based on the notion of a broad family of tailor-made heterogeneous catalysts for liquid-phase oxidations has been tempered by the realization that many of these materials are not stable toward leaching under oxidizing conditions in the liquid phase.

What have we learned from our studies? In the first place we have learned that the conventional practice of recycling a heterogeneous catalyst without observing any

significant loss of activity is by no means proof of heterogeneity. CrAPO-5 could presumably have been recycled 10 or even a 100 times (corresponding to 3 or 30% leaching of available chromium) without any loss of activity (the Trojan horse could still keep releasing its Greek warriors). Rigorous proof of heterogeneity can be obtained only by filtering the catalysts at the reaction temperature before completion of the reaction and testing the filtrate for activity. Moreover, we emphasize that proof of heterogeneous catalysis is not necessarily proof that no leaching occurs. We venture to suggest that manuscripts claiming heterogeneous catalysis in the liquid phase should not be accepted for publication in the absence of rigorous proof of heterogeneity. This applies not only to redox molecular sieves, including encapsulated, grafted, and tethered redox metal complexes, but to all solid catalysts, e.g., the recently reported titanium- and vanadium-containing xerogels⁸⁰ and redox metal ions attached to organic polymers.⁸¹ Only when the problem of catalyst stability has been solved will the potential of heterogeneous catalysts for liquid-phase oxidations be realized.

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